Monitoring Spectral Lines to calibrate LIGO data

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STAR Fellow 2018
LIGO-Hanford Observatory

Outline (0/5)

- Introduction to Gravitational Waves and LIGO
- Introduction to LIGO Differential Arm Length (DARM) Actuation
- DARM Control Loop
- Photon Calibrator
- Spectral Line Monitor upgrades

Outline (1/5)

- <u>Introduction to Gravitational Waves and LIGO</u>
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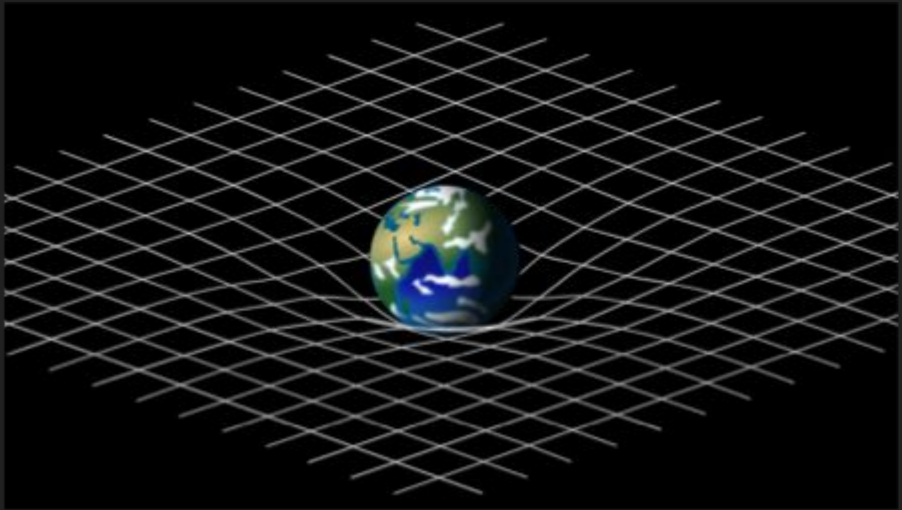
Newtonian Gravity

https://www.flickr.com/

Newtonian Gravity

https://www.flickr.com/

Einsteinian Gravity



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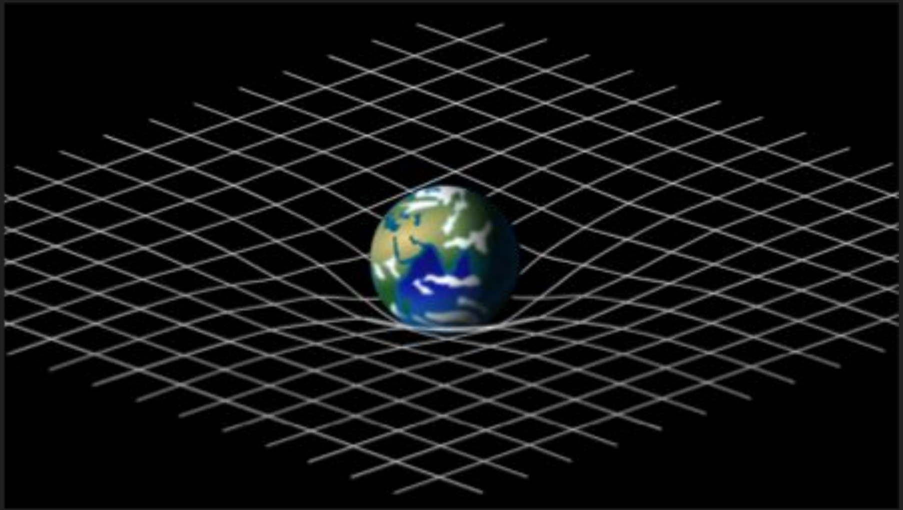
Gravity is the curvature/warping of space and time (collectively spacetime) due to the presence of matter and energy

Static Spacetime



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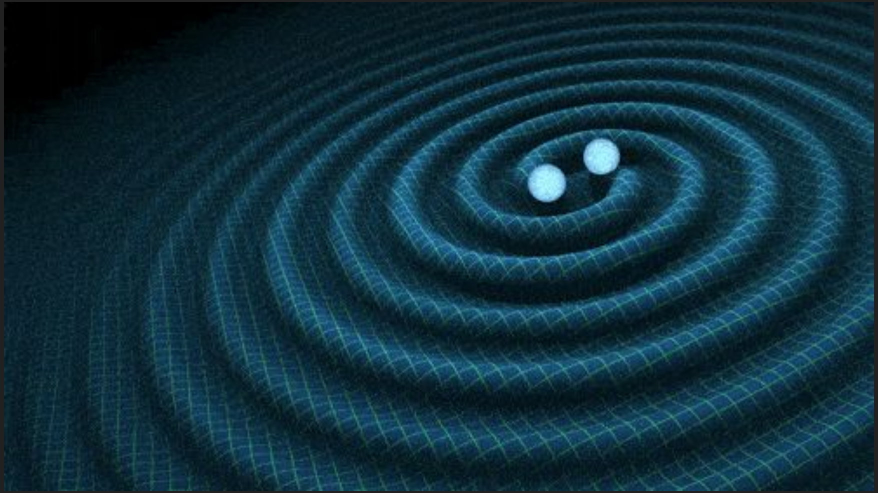
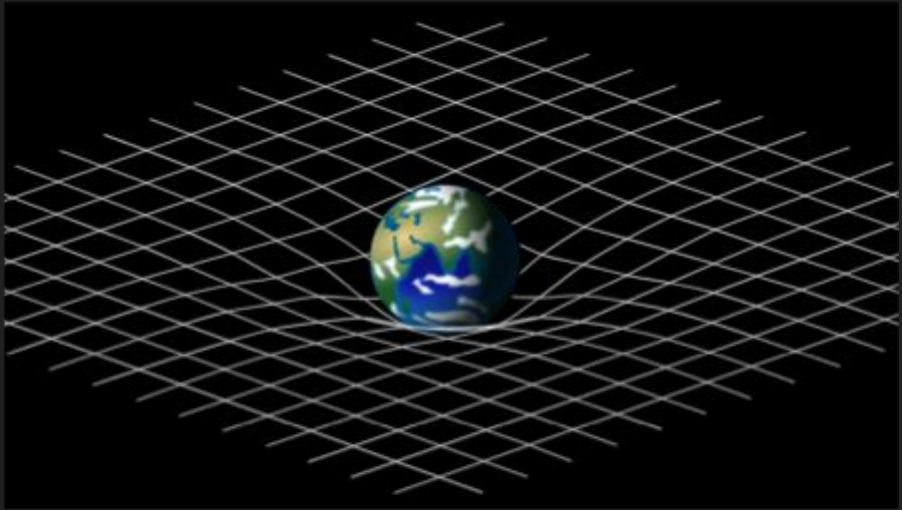
Dynamic Spacetime



Credit: R. Hurt/Caltech/JPL

Static Spacetime



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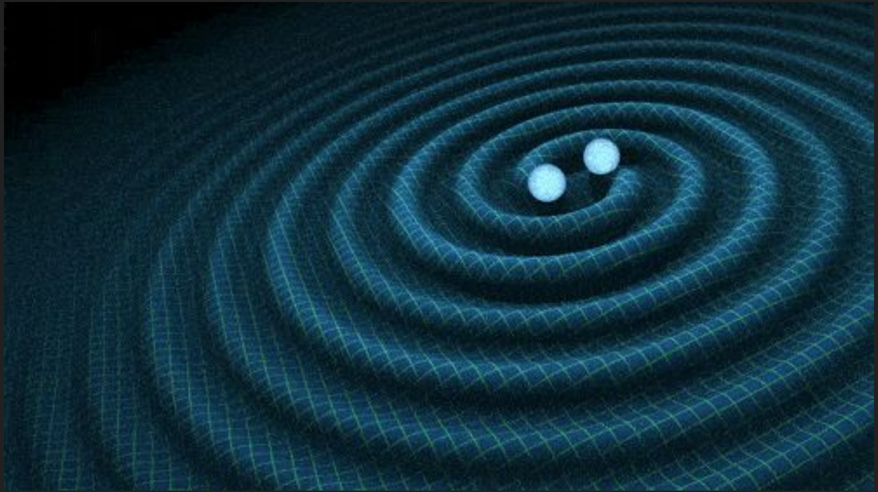
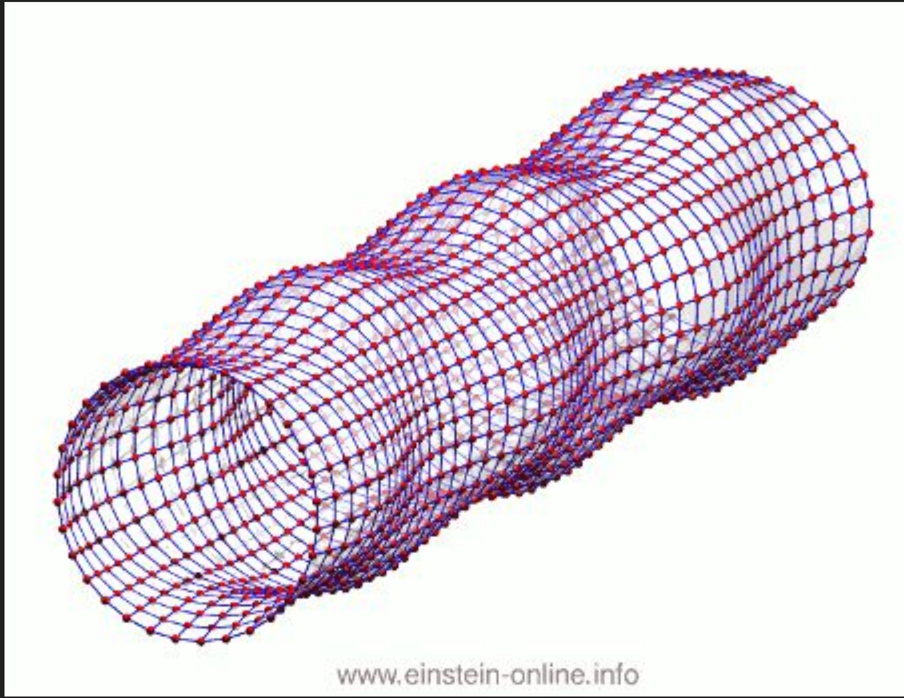
This is what LIGO detects

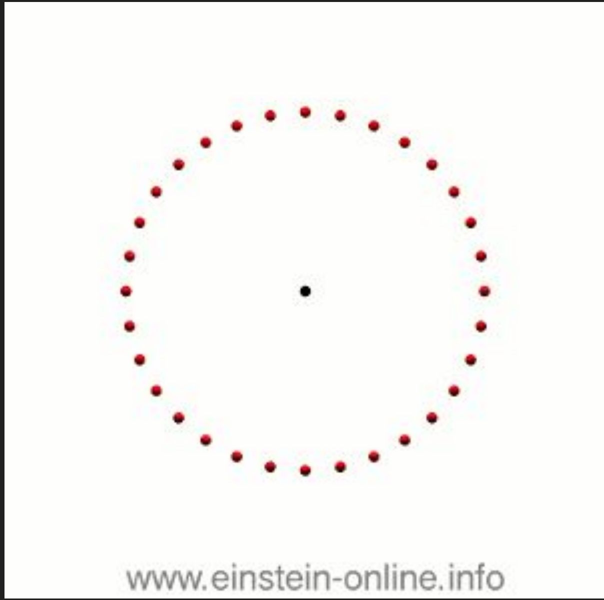
Dynamic Spacetime



Credit: R. Hurt/Caltech/JPL

Signature of a Gravitational Wave on Earth

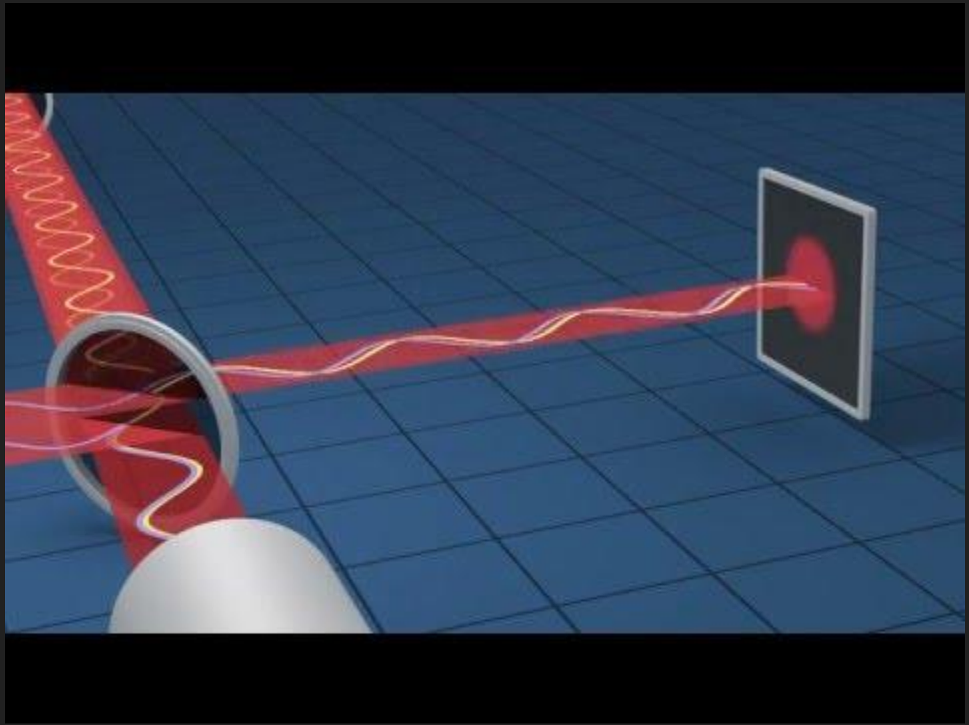




The LIGO Detectors

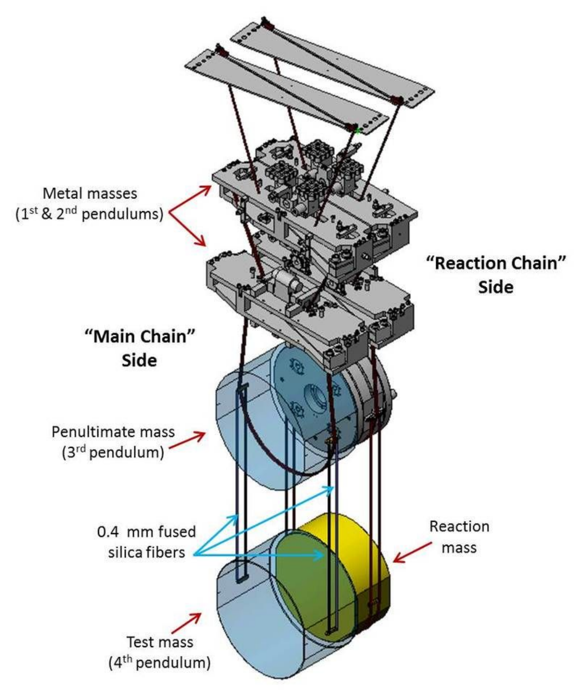
https://commons.wikimedia.org

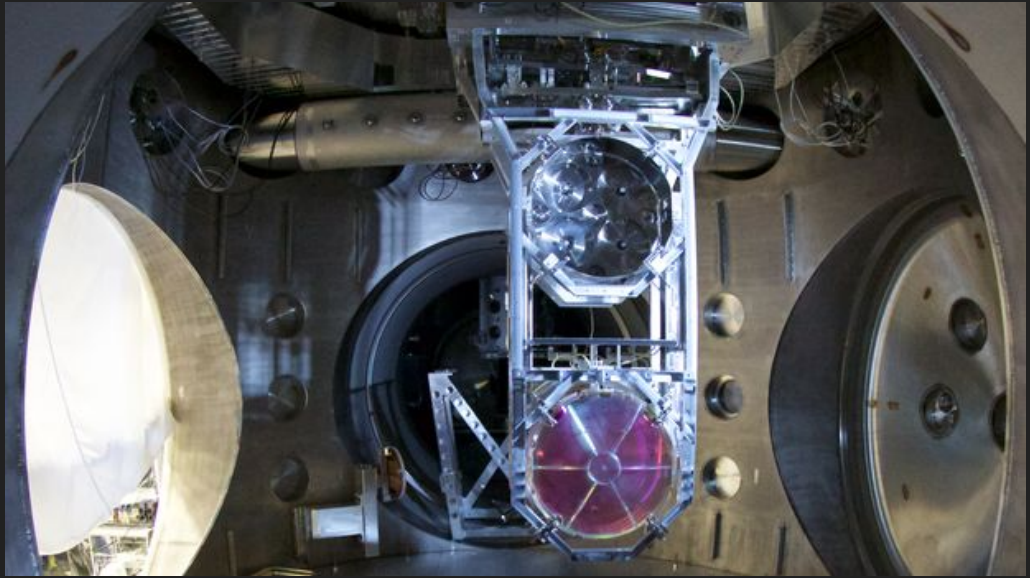
LIGO uses differential arm motion to measure the displacement of spacetime



Displacements on the order of 10^{-18} meters!

The LIGO Test Masses (mirrors) are hung on a quad-suspension pendulum to reduce seismic noise





https://www.ligo.caltech.edu/

Outline (2/5)

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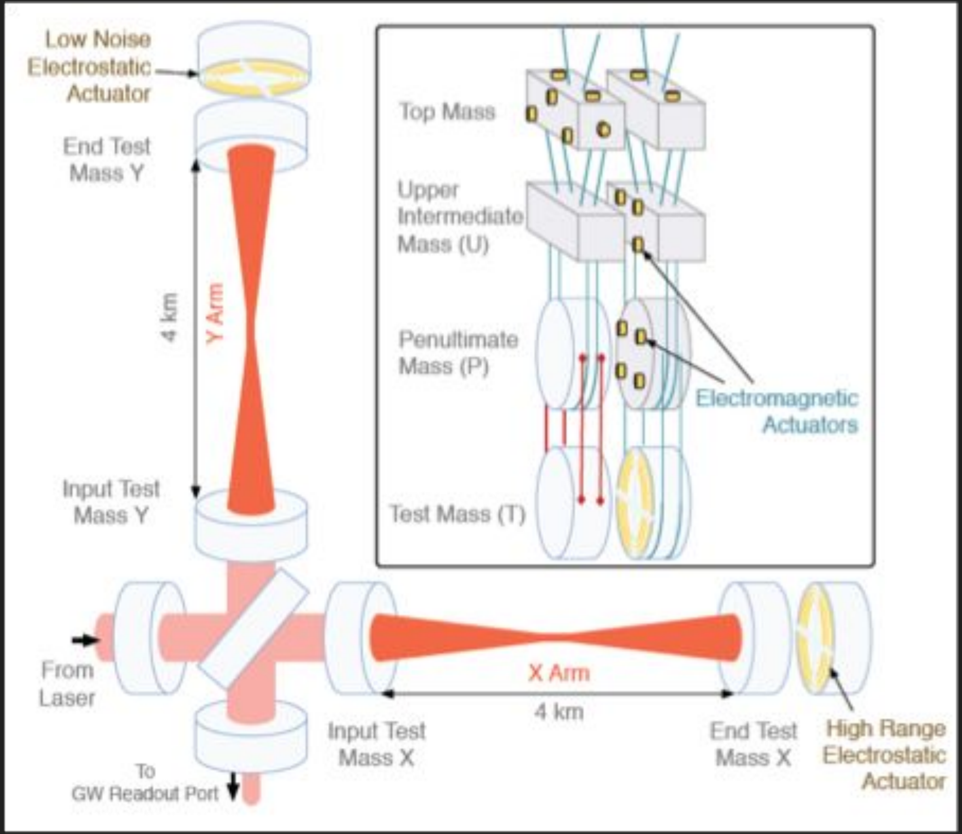
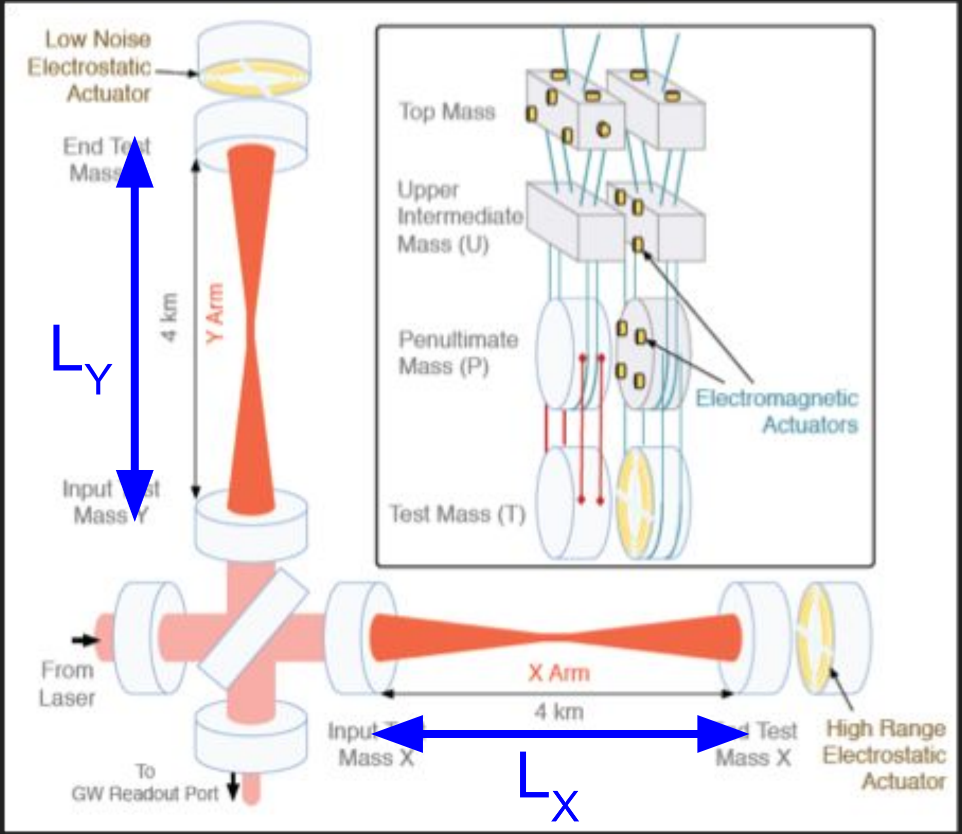
Mirror displacements in LIGO’s quad-suspension pendulum are subdued by actuators

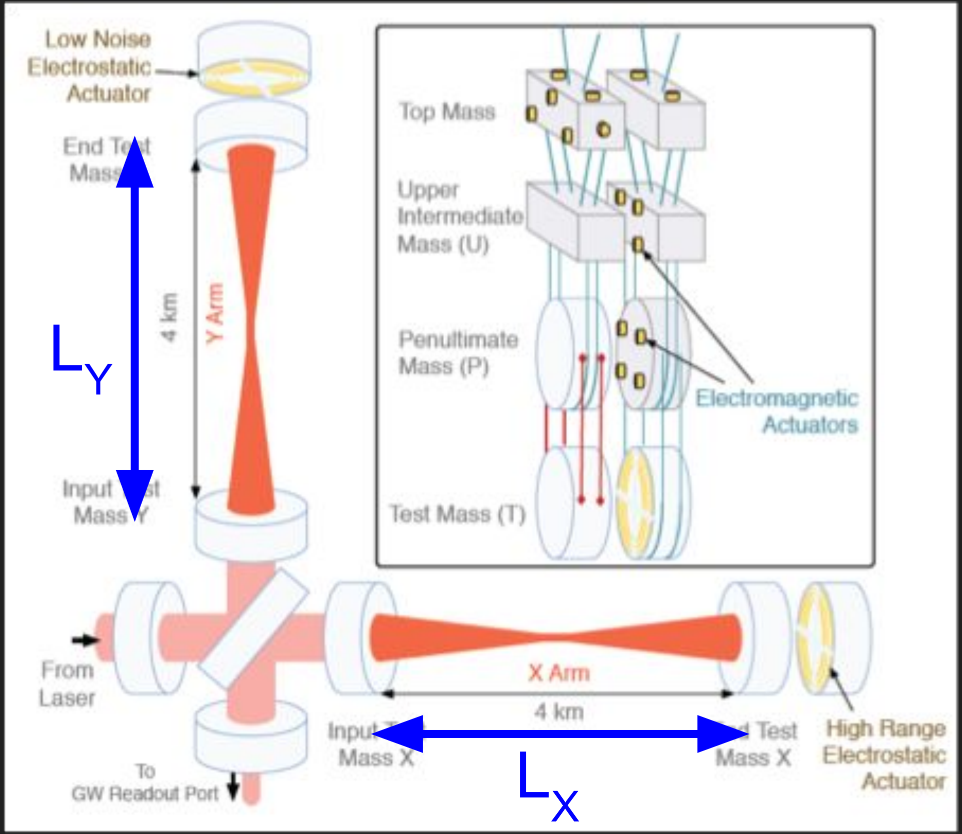


Mirror displacements in LIGO's quad-suspension pendulum are suppressed by actuators



$\Delta L_{ext} = L_X - L_Y$
for free test mass

Mirror displacements in LIGO's quad-suspension pendulum are suppressed by actuators



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ΔL_{ctrl} = displacement from actuators suppressing free motion

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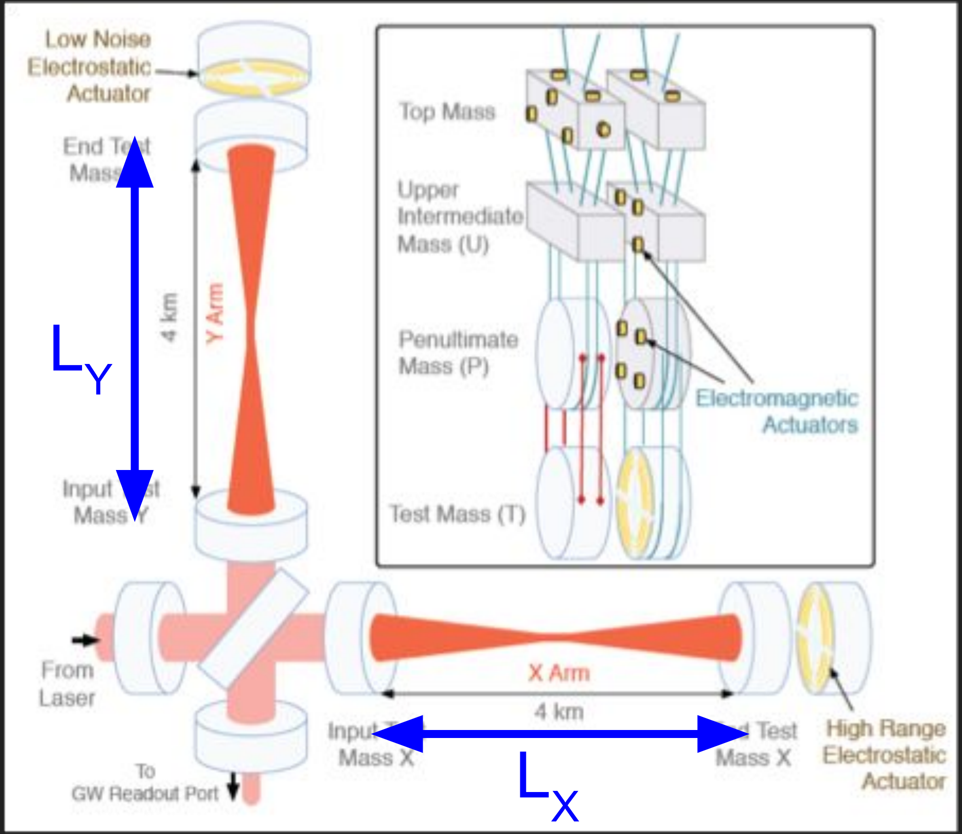

$\Delta L_{ext} = L_X - L_Y$
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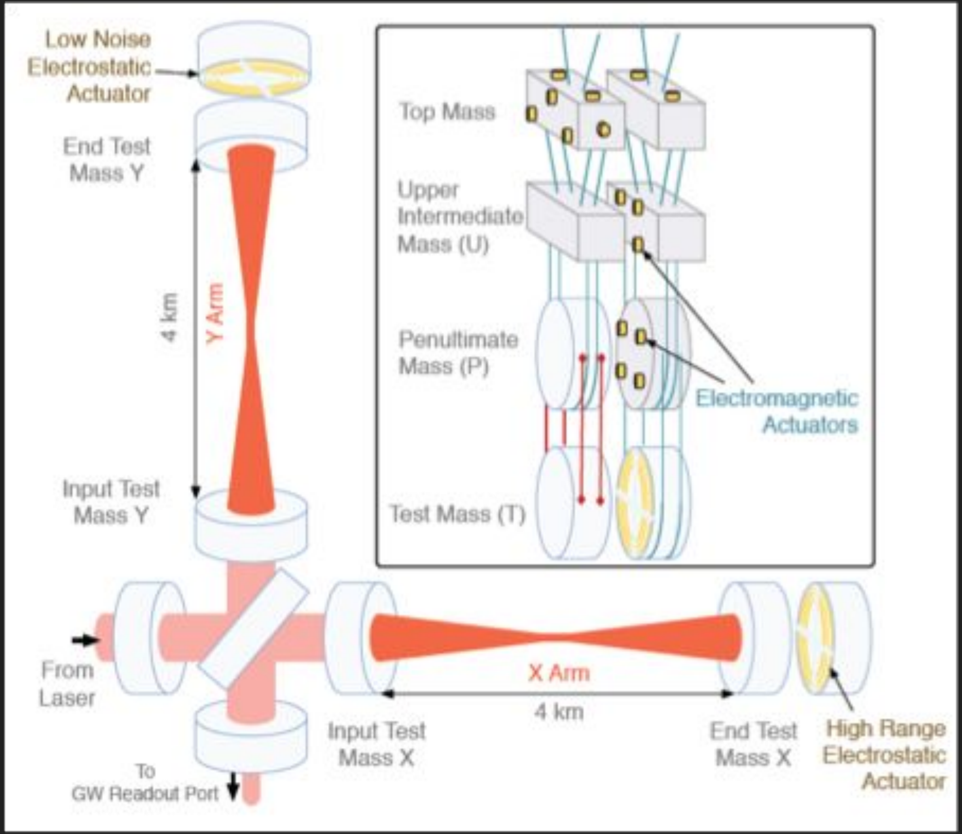
$$\Delta L_{\text{res}} = \Delta L_{\text{ext}} - \Delta L_{\text{ctrl}}$$

Mirror displacements in LIGO's quad-suspension pendulum are suppressed by actuators



Note the quad-suspension pendulum with stages:

- Top mass
- Upper Intermediate Mass (U)
- Penultimate Mass (P)
- Test Mass (T)

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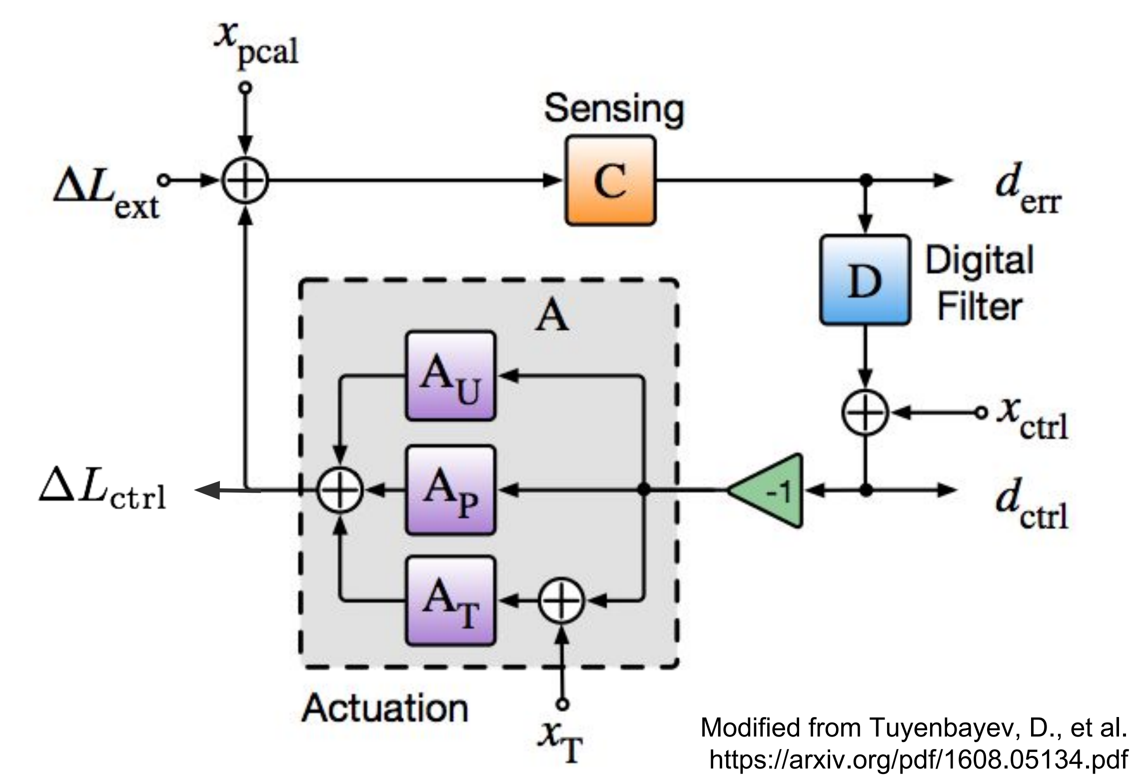
Schematic of differential arm length control loop



Modified from Tuyenbayev, D., et al.
https://arxiv.org/pdf/1608.05134.pdf

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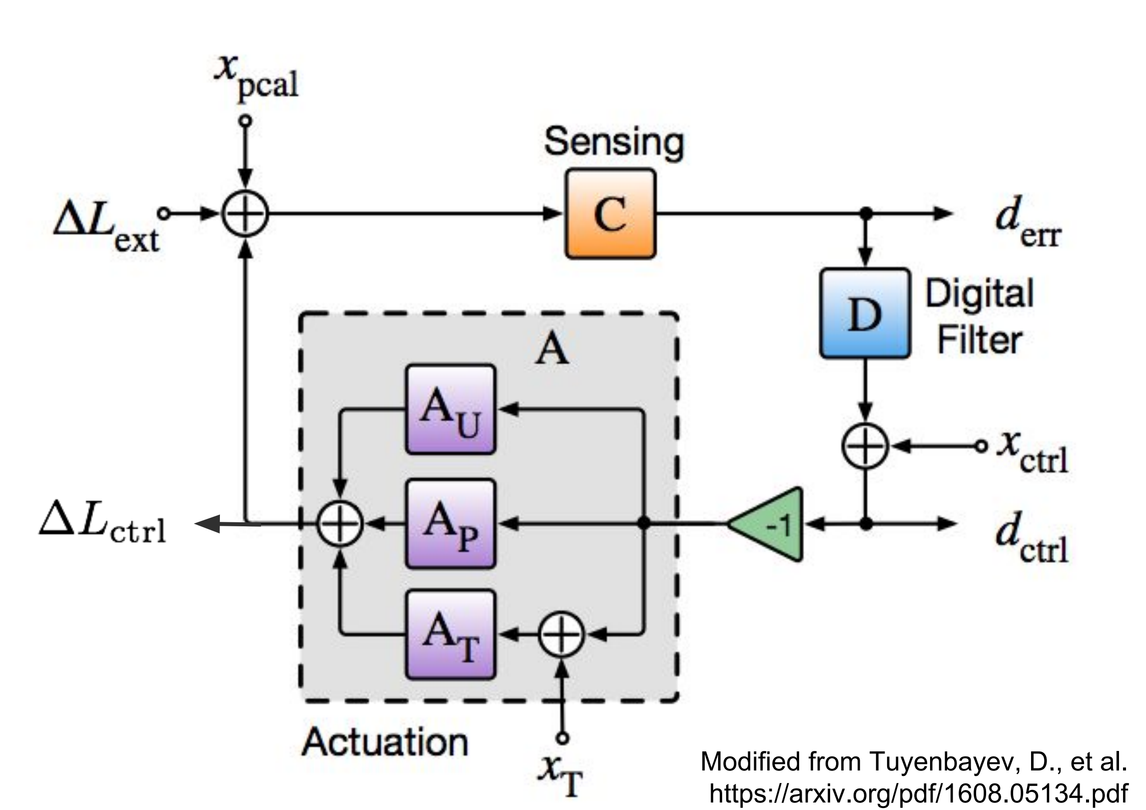

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ΔL_{ext} → unsuppressed differential arm length

ΔL_{ctrl} → control-signal produced diff. arm length

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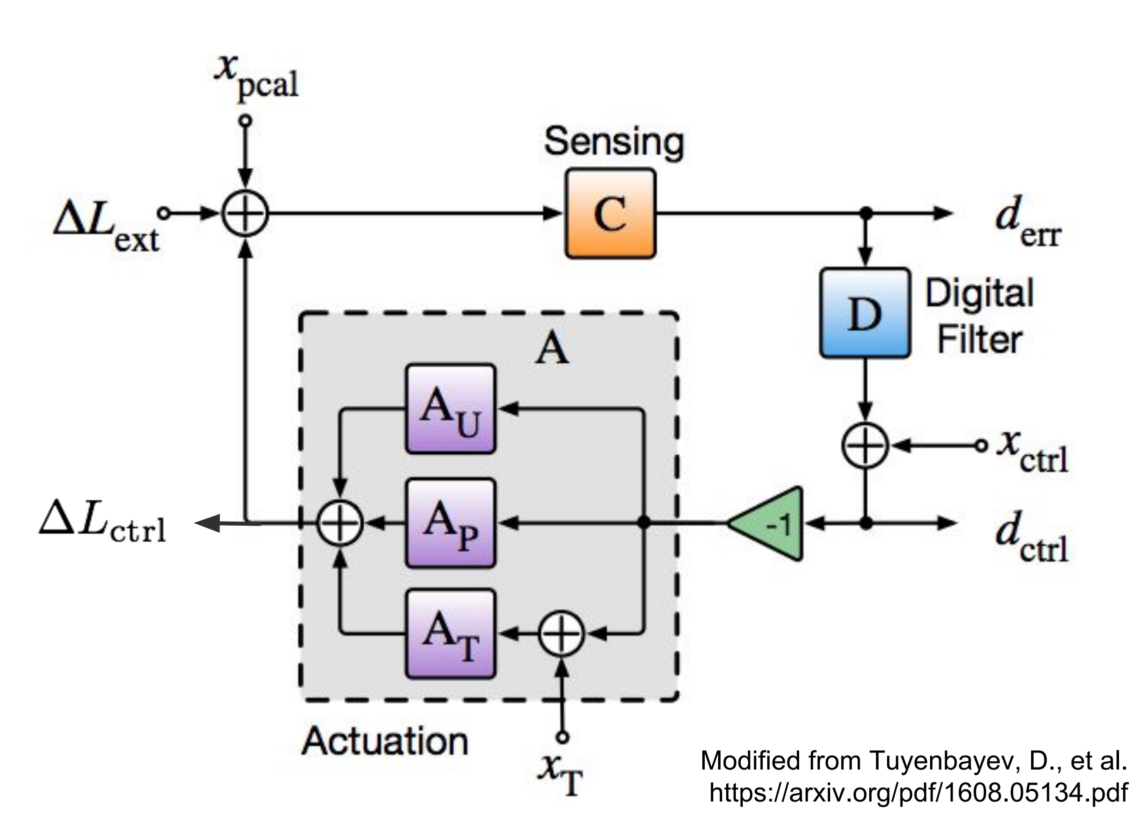

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$$\Delta L_{\text{res}} = \Delta L_{\text{ext}} - \Delta L_{\text{ctrl}}$$

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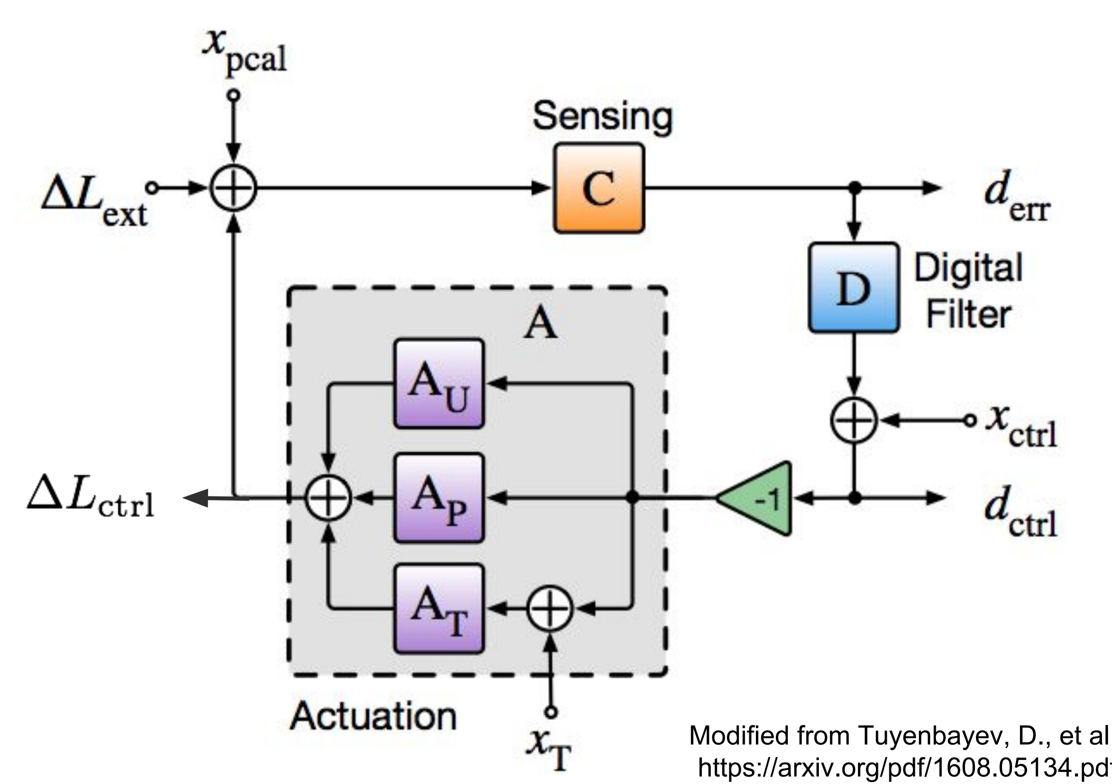

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ΔL_{ext} → unsuppressed differential arm length

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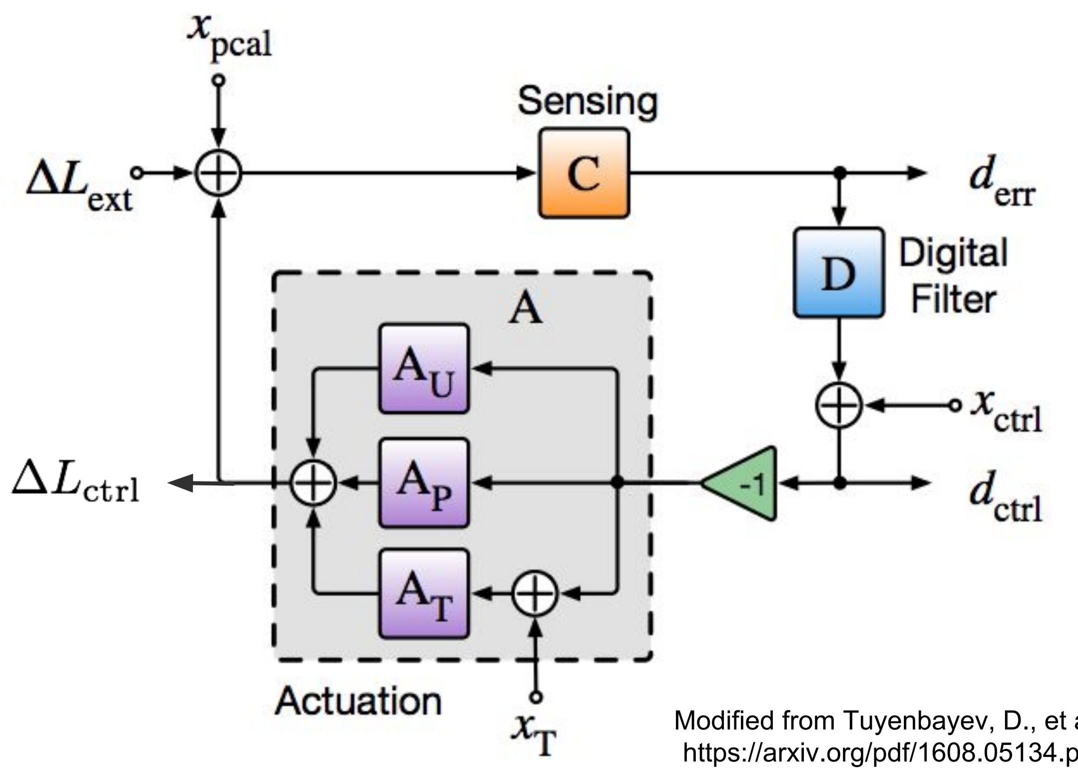
$$\Delta L_{res} = \Delta L_{ext} - \Delta L_{ctrl}$$

d_{err} → digital error signal

d_{ctrl} → digital control signal

Schematic of differential arm length control loop



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$$\Delta L_{res} = \Delta L_{ext} - \Delta L_{ctrl}$$

d_{err} → digital error signal

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$$\Delta L_{ext} = C^{-1} * d_{err}(t) + A * d_{ctrl}(t)$$

Sensing and actuation function models

The sensing function *C(f,t)* is modeled as a single-pole low-pass filter due to the optical response of the signal recycled Fabry-Pérot cavities.

$$C(f,t) = \frac{\kappa_C(t)}{1 + if/f_C} C_R(f) \exp(-2\pi i f \tau_C)$$

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$$C(f,t) = \frac{\kappa_C(t)}{1 + if/f_C} C_R(f) \exp(-2\pi i f \tau_C)$$

The actuation function *A(f,t)* is a function of the gain and normalized frequency dependance of the upper intermediate test mass (U), the penultimate mass (P), and the test mass (T)

$$A(f,t) = \kappa_{\mathrm{PU}}(A_{\mathrm{P},0}(f) + A_{\mathrm{U},0}(f)) + \kappa_{\mathrm{T}} A_{\mathrm{T},0}(f)$$

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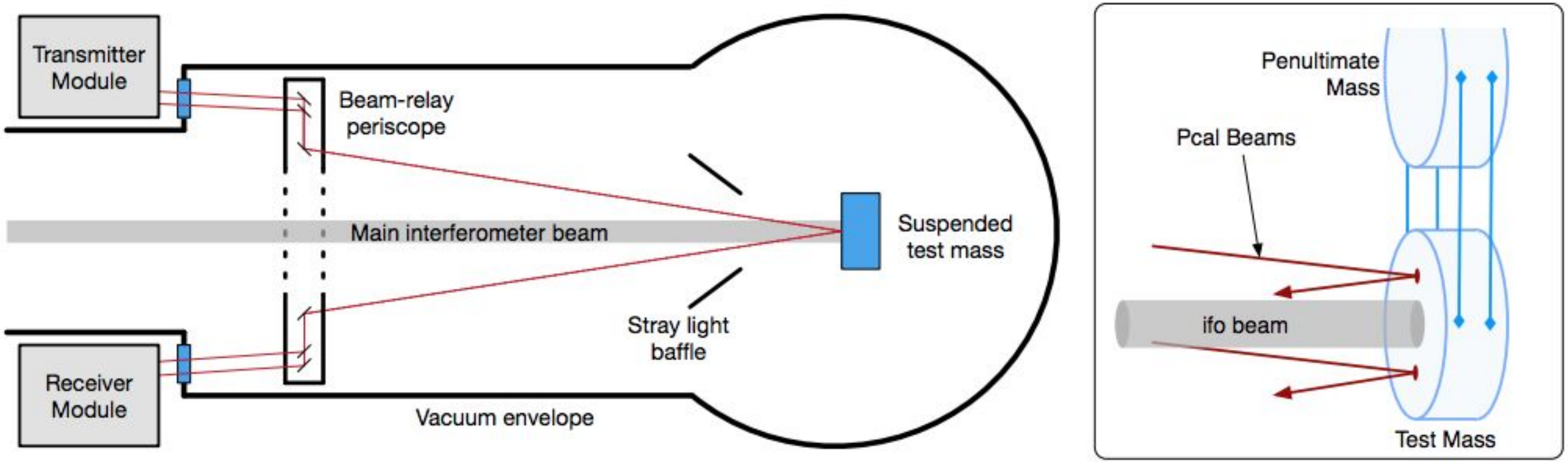
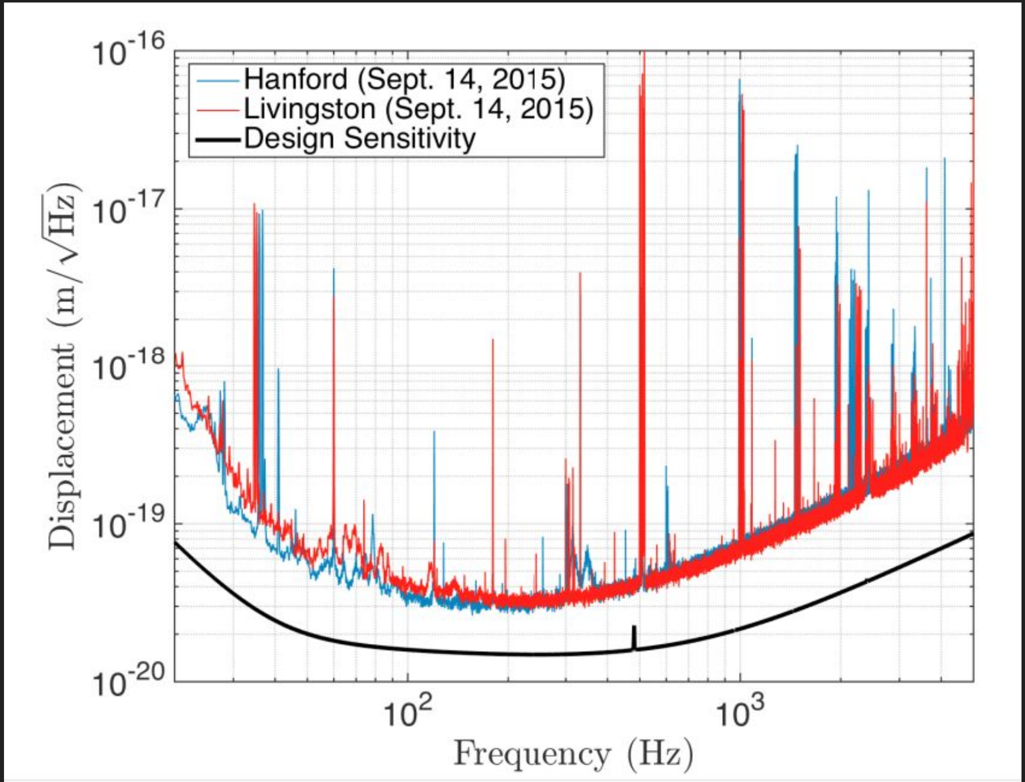
The photon calibrator uses the response of the test mass to an input laser of known power and frequency to calibrate the interferometer



Karki, S., et. al. https://arxiv.org/pdf/1608.05055.pdf

The photon calibrator injects calibration lines at ~36 Hz, 331 Hz, 1083 Hz, and 3001 Hz



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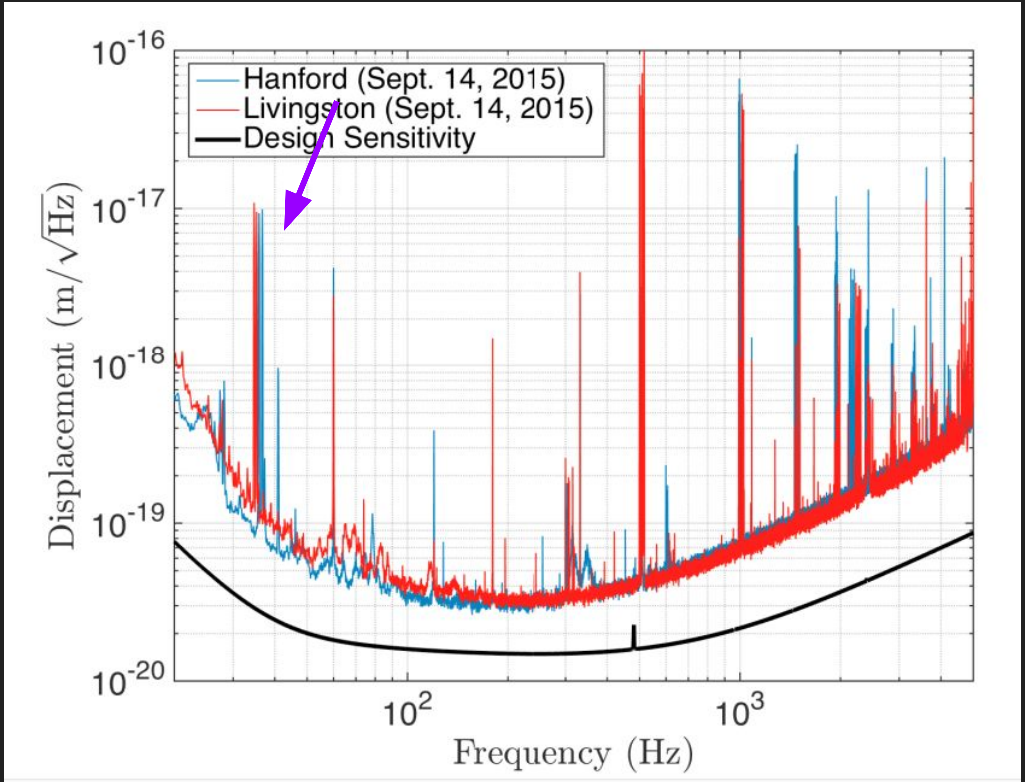

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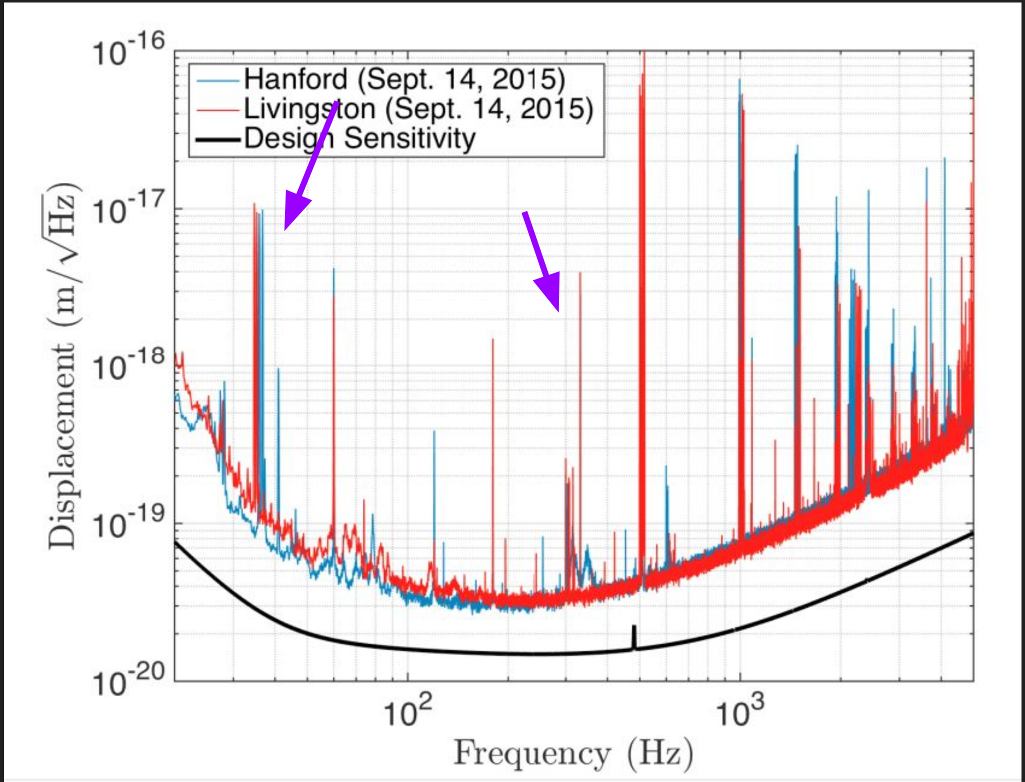

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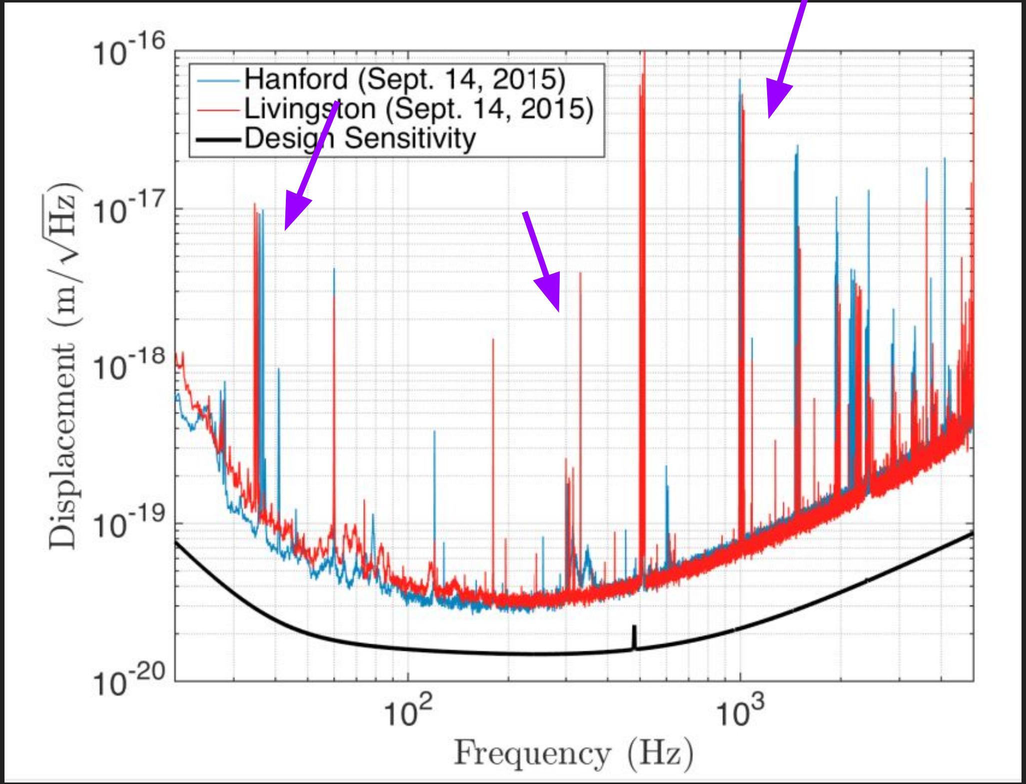

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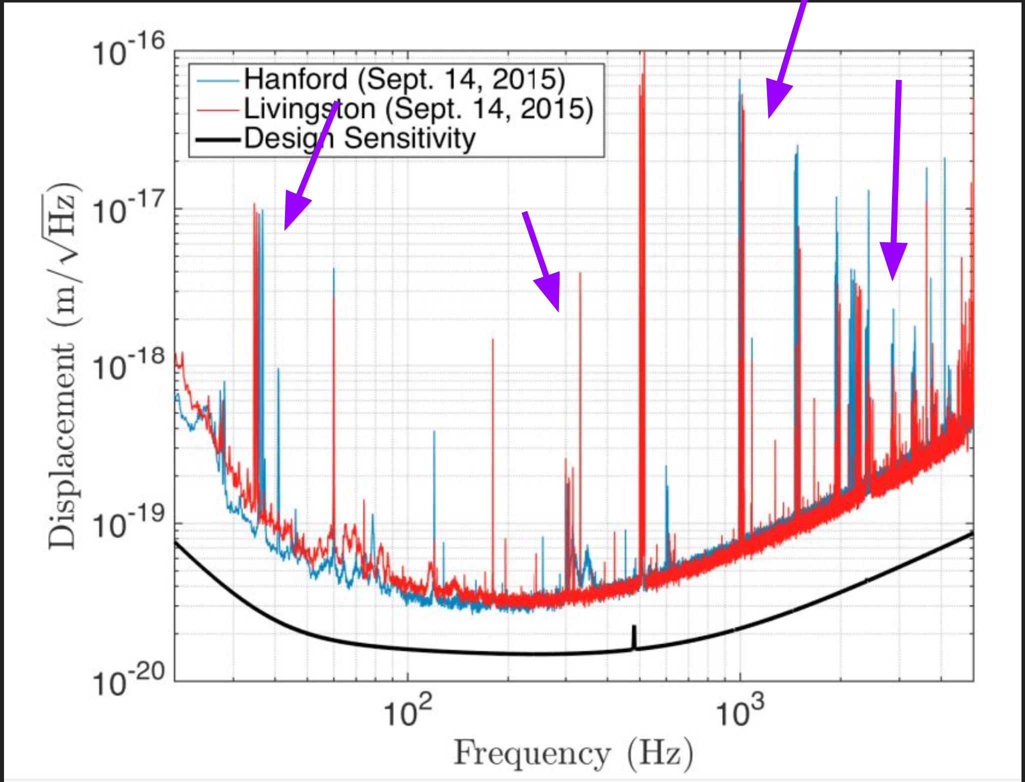

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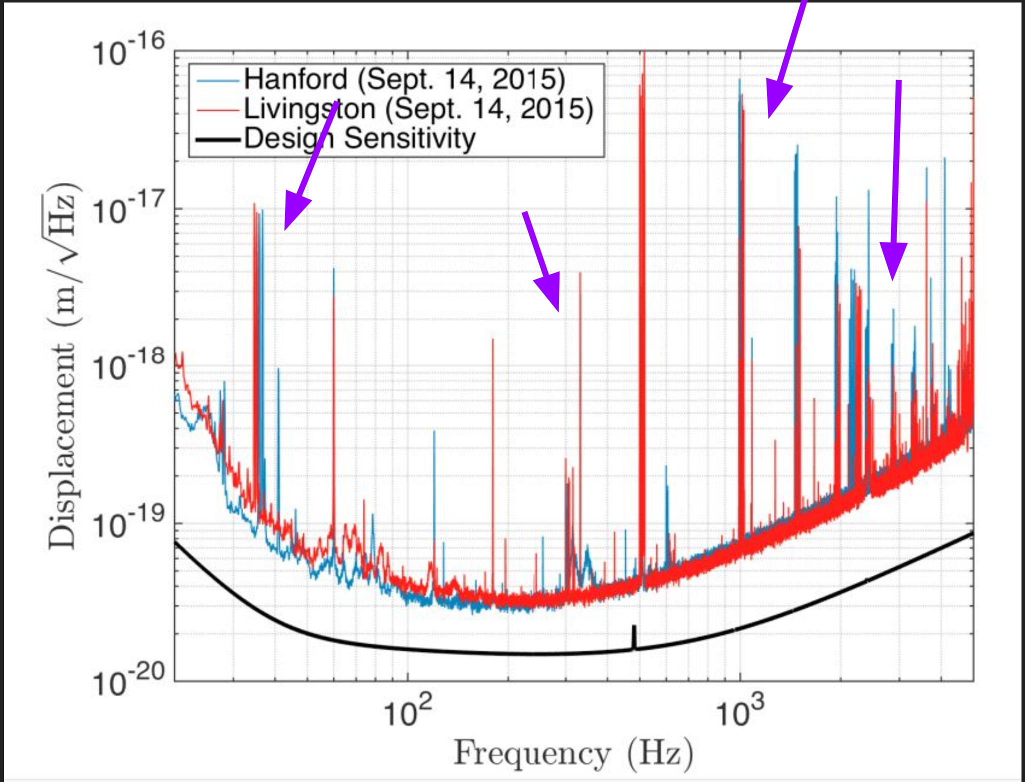

Calibration lines are also injected by the actuators (i.e., not Pcal) at ~35 Hz (x_{ctrl}) and ~37 Hz (x_{tst})

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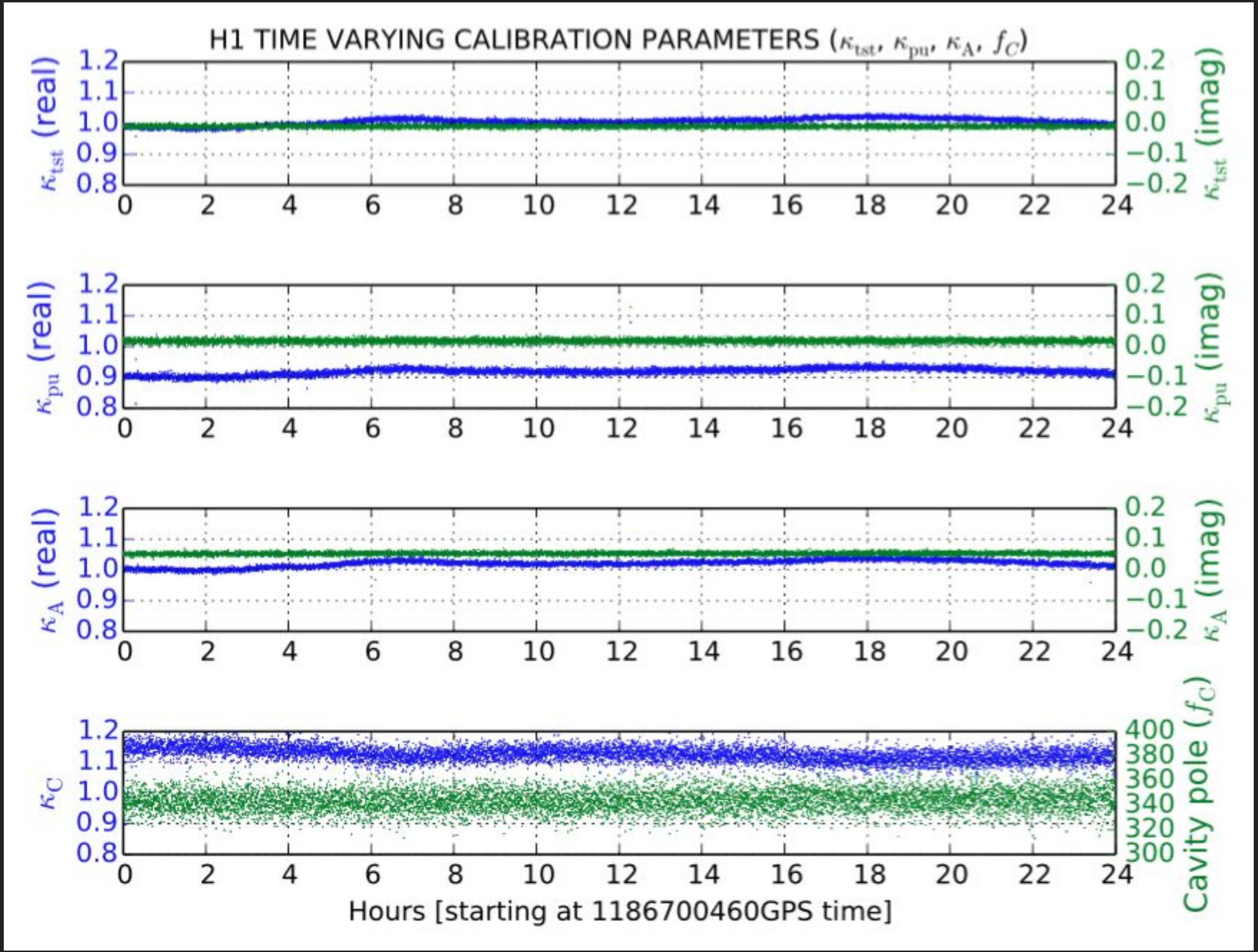
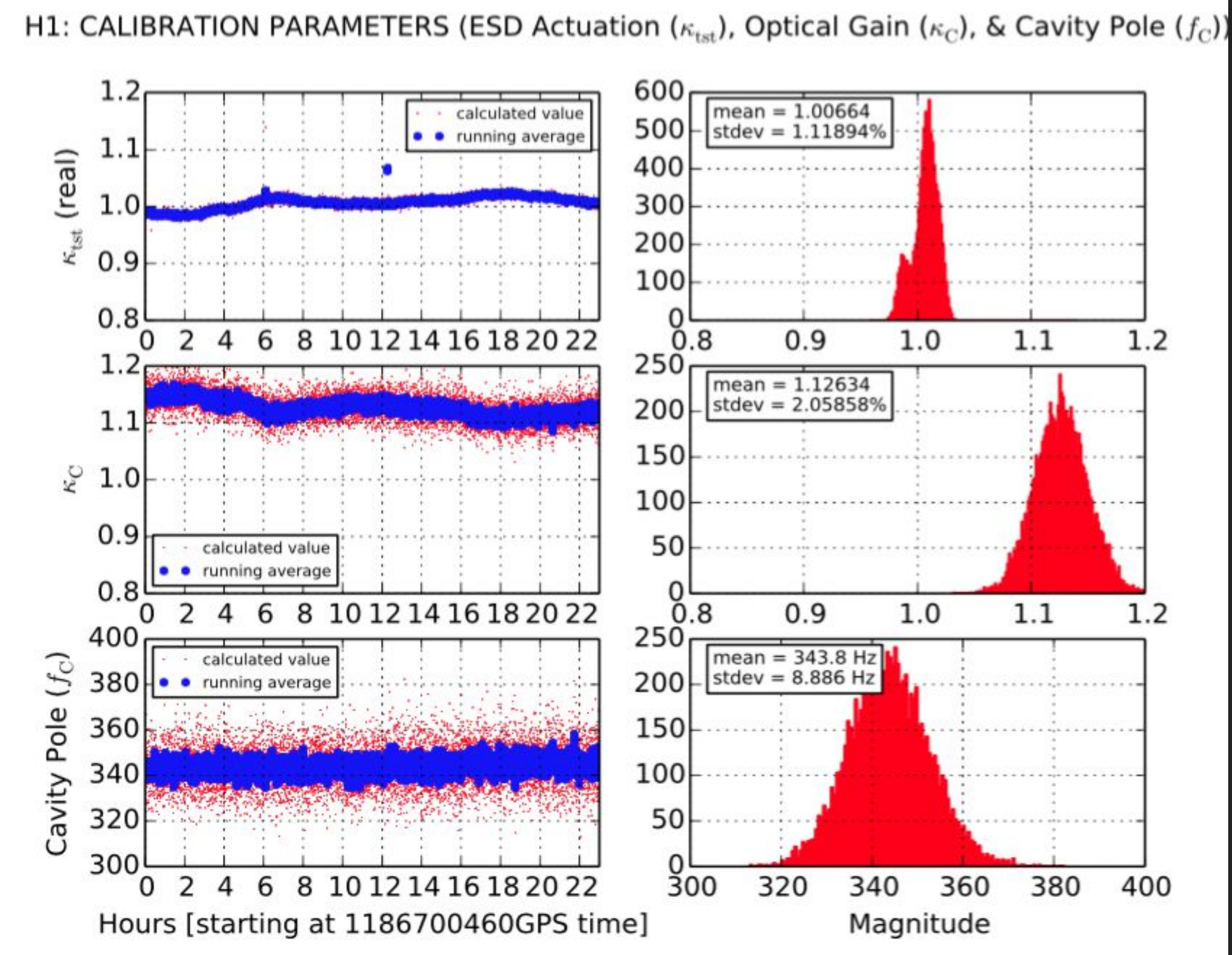
The Spectral Line Monitoring (SLM) tool functionality

- Tracks the amplitude, phase, and power spectral density of specified frequencies in the LIGO data channels
    - Designed to be a once-per-day diagnostic, not real time
- Creates independent plots of the time varying kappa factors from the sensing and actuation functions, as well as the cavity pole frequency as a function of time
- Calculates and plots ratios of GDS to Pcal and GDS to Front End (DARM_ERR, DARM_CTRL) calibration line amplitudes to discern potential discrepancies
- Plots ratios of transmitted and received Pcal light to discern potential clipping
- Plots other parameters and ratios relevant to Pcal

Example Kappa Plot 1

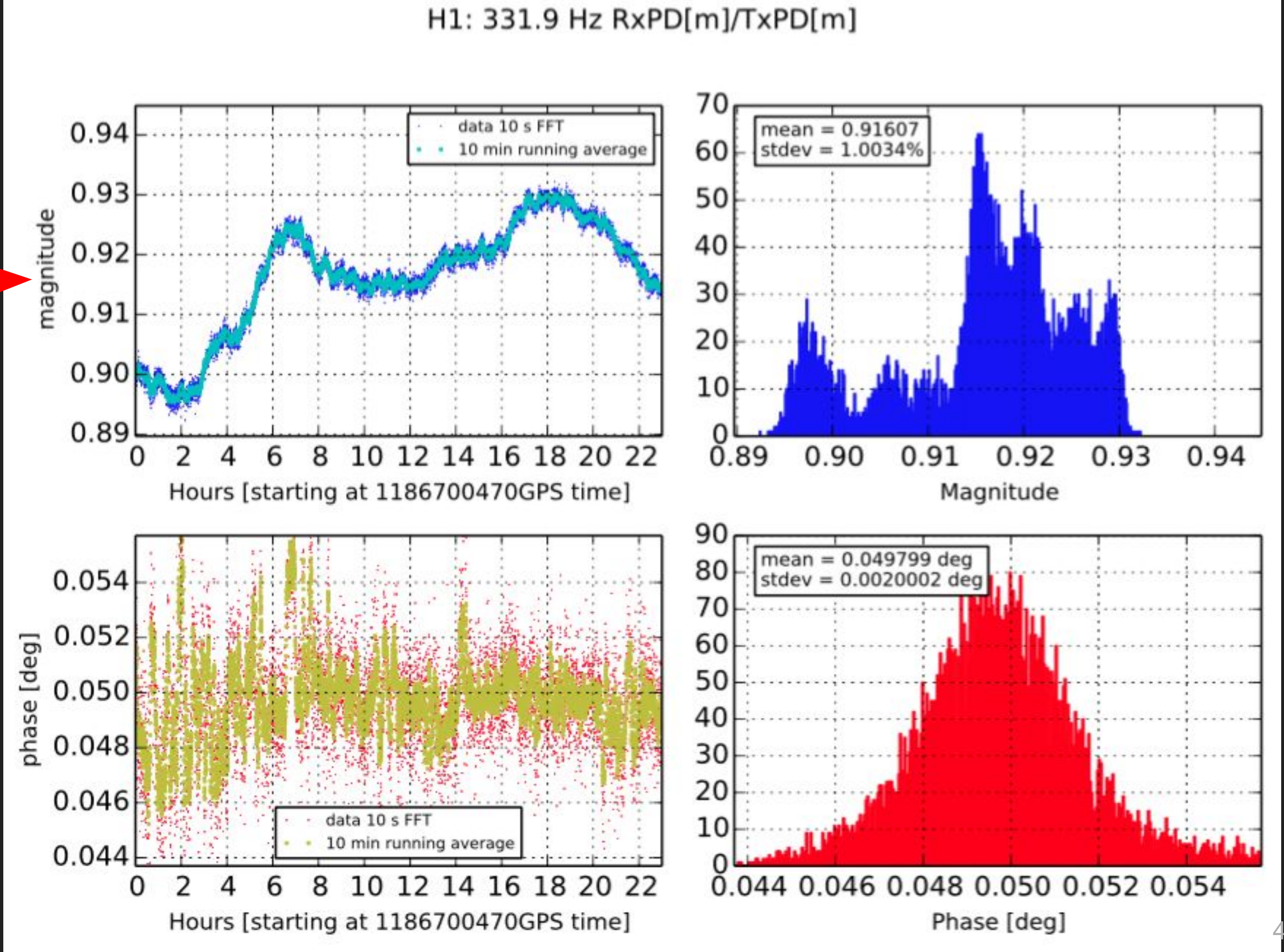


Example Kappa Plot 2



Among other uses, SLM can be used to see light clipping with Pcal

This ratio should always be 1



Conclusion: Not all of the light transmitted by Pcal was received. Some of the light must be clipping somewhere.

Comparison of current vs. updated SLM Functionality

Current Functionality

- SLM data only output to ascii text file
- EPICS channels needed to be manually updated
- Plotting tools all in MATLAB
  - Needs to recomplile every time it is run
  - Proprietary...licence issues

New Functionality

- SLM data output to both ascii text files *and* gwf frame file (e.g., for discovery by NDS2)
  - Allows for easier integration with tools used by control room for plotting
- EPICS channels are updated automatically once per day
- Plotting tools now in Python
  - Does *not* need to recompile every time
  - Free, easier to maintain and integrate with other calibration code

Areas for improvement in SLM

- Hardcoded to do six specific frequencies. If you wanted to add more, then the SLM code would need to be changed.
- Automatically produce plots that compare the kappa values calculated by SLM to the kappa values recorded in online calibration pipeline

Thank you!

This material is based upon work supported by the National Science Foundation through the Robert Noyce Teacher Scholarship Program under Grant #1418852. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. The research was also made possible by the California State University STEM Teacher and Researcher Program, in partnership with Chevron (www.chevron.com), the National Marine Sanctuary Foundation (www.marinesanctuary.org), and the LIGO Hanford Observatory.

References

E. Anders *et al.* LIGO SURF Final Report: Spectral Line Monitoring Tool. (2013) [LIGO-P11300120-v2].

S. Karki *et al.* Rev. Sci. Instrum. **87.** no.11, 114503 (2016) doi:10.1063/1.4967303 [arXiv:1608.05055 [astro-ph.IM]].

D. Tuyenbayev *et al.*, Class. Quant. Grav. **34**, no. 1, 015002 (2017) doi:10.1088/02649381/34/1/15002 [arXiv:1608.05134 [astro-ph.IM]].